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Failure Probabilities of FRP Strengthened RC Column to Blast Loads

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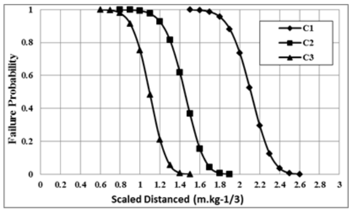
Graphical abstract



Abstract

Probability analysis is commonly used to estimate the structural damage subjected to the static loads as well as dynamic loads such as earthquakes, wind and blast loads. Blast loads is difficult to predict accurately due to the parameters that influence the uncertainty in the blast shock wave propagation and shock wave-structures interaction. However, probability analysis of the structural damage can be carried out by considering all the blast load parameters and the structural properties. Instead, scale distance factors (producing various pressures and impulses) also affect the uncertainty of variations in structure damage to blast load and analysis of blast-resistant design. This study presents a reliability analysis of unstrengthened and FRP strengthened RC columns to blast loads. Three different parameter examples of unstrengthened reinforced concrete (RC) columns and Fibre Reinforced Polymer (FRP) strengthened RC column are used. The failure probabilities of RC columns under different level blast load corresponding to different range of scaled distances are estimated and presented. The results indicate reliability analysis gives range of scaled distances with different probabilities of column collapse.

Keywords: Failure probabilities; RC column; blast; scale distance factors; FRP; empirical formulae

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■1.0 INTRODUCTION

Reinforced concrete (RC) column can be subjected to extreme loadings such as blast wave, shock wave or direct impact. In order to resist progressive collapse, structural damage and preventing injuries against these extreme loading, the Fiber Reinforced Polymer (FRP) strengthening concepts have been widely used to strengthen the RC column structures [1,2,3]. Its effectiveness in strengthening RC structures to resist blast and impact loads have been proven in both numerical and experimental studies. However, there are limited systematic studies that directly correlate the increase in structural capacities in resisting the blast loads with the strengthening measures, such as the strengthening materials, layers of FRP applied and types of epoxy used.

The reliability and failure probability analyses of RC structural components are often used to quantify structural performance under various blast loading scenarios [4,5]. By developing blast failure probabilities for FRP strengthened structures, the quantitative correlation between minimum scaled distance, z required to reaching a particular level of damage, D of FRP strengthened and unstrengthened columns can be plotted. In addition, the boundary between direct shear failure and flexural failure of the column as a function of the blast loading duration can be determined. Other studies, also discussed the risk acceptability and cost effectiveness for infrastructure protection using probability analysis [8].

In this study, the blast failure probabilities of unstrengthened and FRP strengthened RC columns are estimated using structural component reliability analysis method. The P-I curves developed by an authors in a previous study [1] are used as the basis in assessing the RC column damage. P-I diagrams relate the level of damage suffered by a structural member when exposed to different combinations of pressure and impulse created by explosives. It has been developed by many researchers using different methods for different structural components. These include development of P-I curves based on experimental data [9], based on SDOF analysis [10] and numerical analysis [1,11]. In these analyses, random variations of unstrengthened and FRP strengthened RC column dimensions and material and FRP properties, as well as the random variations of blast loading estimations corresponding to different scaled distances are considered. The range of the blast loadings to cause any damage to sure damage of the RC columns are derived from the reliability analyses. The results presented in this study can be used to assess the failure probabilities of individual RC columns. They can also be incorporated in a system reliability analysis to predict the probability of progressive collapse of building structures.

■2.0 P-I DIAGRAMS FOR BLAST DAMAGE ASSESSMENT OF FRP STRENGTHENED RC COLUMNS

A simplified numerical technique has proposed by Shi *et al*. [11] to develop the P-I diagrams for RC columns. They define *D* as Eq. (1),

$$D = 1 - \frac{P_{Residual}}{P_{Design}} \quad (1)$$

where $P_{Residual}$ is the residual axial load-carrying capacity of the damaged RC column and P_{Design} is the maximum axial load carrying capacity of the undamaged RC column [2,12]. Different values of *D* are correlated to different damage degrees i.e. D = 0 - 0.2 is low damage; 0.2 - 0.5 is medium damage; 0.5 - 0.8 is high damage and 0.8 - 1 is collapse. An examination of fitted P-I diagrams in [1,11] finds that P-I diagram for RC columns can be expressed analytically as

$$(P - P_O)(I - I_O) = 12\left(\frac{P_O}{2} + \frac{I_O}{2}\right)^{1.5} \quad (2)$$

where P_O and I_O are the pressure and impulse asymptotes respectively. In this study, empirical formulae to predict P_O and I_O are derived from a series of verified numerical results for RC columns with and without FRP strengthening using the least squares-fitting method [1]. They are expressed as a function of transverse reinforcement ratio ρ_s, longitudinal reinforcement ratio ρ, concrete strength f_c, column height *H*, column depth *h*, column width *b*, FRP wrap and strip strength f_{wrap} and f_{strip} and FRP wrap thicknesses t_{wrap}. Figure 1 shows the RC column details and the FRP strengthened RC columns are illustrated in Figure 2. The empirical formulae are derived using curve fitting method.

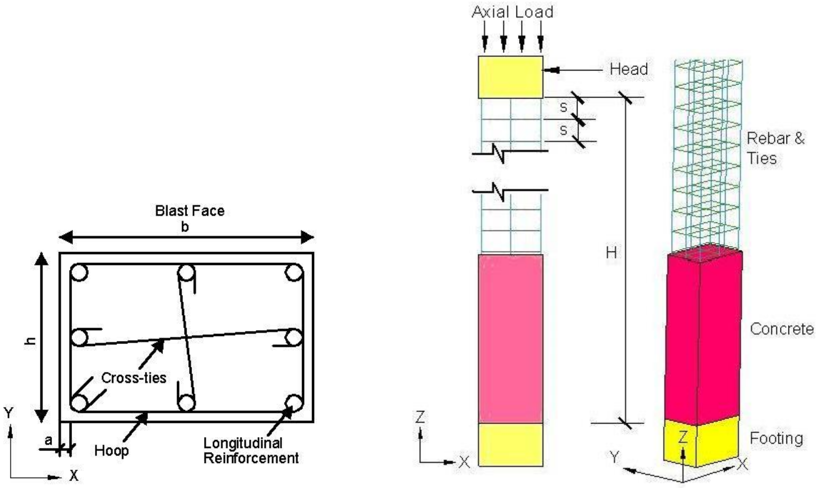
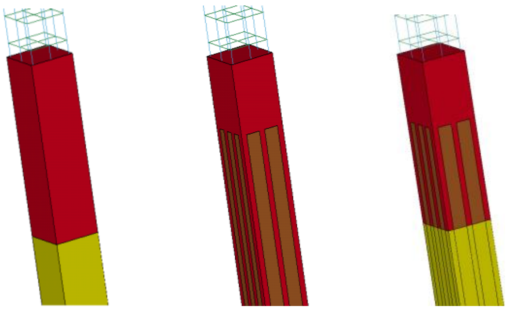


Figure 1 Details of RC column



(a) (b) (c)

Figure 2 FRP strengthened RC column configurations, (a) FRP wrap, (b) FRP strips, and (c) combination FRP strips and wrap

The empirical formulae of pressure and impulse asymptotes of P-I diagrams can be derived as Equations (3) until (8) which are obtained by series of numerical simulations.

$$P_O(0.2) = 7.25 f_{cu} + 2.37d - 0.147H - 0.414b + 7342.47\rho + 10073.44\rho_s + \alpha_1 \quad (3)$$

$$I_O(0.2) = 25 f_{cu} + 7.289d - 0.158H - 0.168b + 19261.3\rho + 44864.881\rho_s - 2398.62 + \alpha_2 \quad (4)$$

$$P_O(0.5) = 2\boldsymbol{f_{cu}} + 3.174\boldsymbol{d} - 0.217\boldsymbol{H} - 0.445\boldsymbol{b} + 15786.72\rho + 18137.95\rho_s + 210 + \alpha_3 \tag{5}$$

$$I_O(0.5) = 27.5\boldsymbol{f_{cu}} + 9.75\boldsymbol{d} - 0.168\boldsymbol{H} - 1.776\boldsymbol{b} + 13121.77\rho + 29433.94\rho_s - 1848.178 + \alpha_4 \tag{6}$$

$$P_O(0.8) = 11\boldsymbol{f_{cu}} + 3.456\boldsymbol{d} - 0.268\boldsymbol{H} - 1.552\boldsymbol{b} + 14753.44\rho + 8924.068\rho_s + 851.90 + \alpha_5 \tag{7}$$

$$I_O(0.8) = 59\boldsymbol{f_{cu}} + 13.16\boldsymbol{d} - 0.43\boldsymbol{H} - 0.26\boldsymbol{b} + 1091.78\rho + 489.97\rho_s - 3302.33 + \alpha_6 \tag{8}$$

where $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6 = 0$ for non-retrofitted RC columns, while for FRP strengthened RC columns,

$$\alpha_1 = \exp\left(0.000169 f_{strip} + 0.000423 f_{wrap} + 0.252 t_{wrap} + 3.114\right) \tag{9}$$

$$\alpha_2 = \exp\left(0.000163 f_{strip} - 0.000132 f_{wrap} + 0.307 t_{wrap} + 5.09\right) \tag{10}$$

$$\alpha_3 = 0.0539\boldsymbol{f_{strip}} - 0.00909\boldsymbol{f_{wrap}} + 54.53\boldsymbol{t_{wrap}} + 32.302 \tag{11}$$

$$\alpha_4 = \exp\left(-0.00000295 f_{strip} + 0.00124 f_{wrap} + 0.382 t_{wrap} + 2.524\right) \tag{12}$$

$$\alpha_5 = \exp\left(0.000189 f_{strip} + 0.0000795 f_{wrap} 0.16 t_{wrap} + 4.286\right) \tag{13}$$

$$\alpha_6 = \exp\left(0.0000868 f_{strip} + 0.0012 f_{wrap} + 0.549 t_{wrap} + 2.068\right) \tag{14}$$

The above empirical formulae are valid for reinforcement steel strength 550 MPa. For reinforcements with other strengths, the equivalent longitudinal and transverse steel area A_{se} should be used when calculating the respective reinforcement ratio.

$$\boldsymbol{A_{se}} = \frac{\boldsymbol{f_y}}{550}\boldsymbol{A_s} \tag{15}$$

In this study, three example of unstrengthened RC column and FRP strengthened are considered. The properties of unstrengthened RC columns are given in Table 1 while the details of FRP strengthened RC columns are listed in Table 2. It should be noted that all FRP strengthened RC columns other details are as C1. In case of FRP strengthened RC column, C4 is strengthened RC column with FRP wrap, strengthened RC column with FRP strips is C5 and C6 is strengthened RC column with FRP wrap and strips.

Table 1 Parameters for unstrengthened RC columns

Column	**Width b (mm)**	**Height H (mm)**	**Depth h (mm)**	**Concrete strength f_{cu} (MPa)**	**Longitudinal Reinforcement ratio, ρ**	**Transverse Reinforcement ratio, ρ_s**
C1	450	3000	450	25	0.020	0.010
C2	550	3500	550	35	0.025	0.015
C3	650	4000	650	45	0.030	0.020

Table 2 Parameters for FRP strengthened RC columns

Column	**FRP wrap strength f_{wrap} (MPa)**	**FRP strip strength f_{strip} (MPa)**	**FRP thickness t_{wrap} (mm)**
C4	2080	NA	3
C5	NA	2280	3
C6	2080	2280	3

Figure 3 shows the P-I curves for column C1, C2 and C3 generated using Equations (2), (7) and (8) at level of damage D = 0.8. The findings show that C3 has asymptotic values higher than C1 and C3. It requires scaled distance of 1.0 m/kg$^{-1/3}$ to reach the P-I curve boundary and scaled distance of 1.3 m/kg$^{-1/3}$ and 1.6 m/kg$^{-1/3}$ are required to fail column C1 and C2, respectively.

P-I diagrams for FRP strengthened RC columns for C4, C5 and C6 are shown in Figure 4 developed by Equations (2), (7), (8), (13) and (14). All FRP strengthened columns are using column C1 details. As shown in the figure, a significant improvement is obtained by utilizing the FRP which C6 is the best strengthening technique followed by C4 and then C5.

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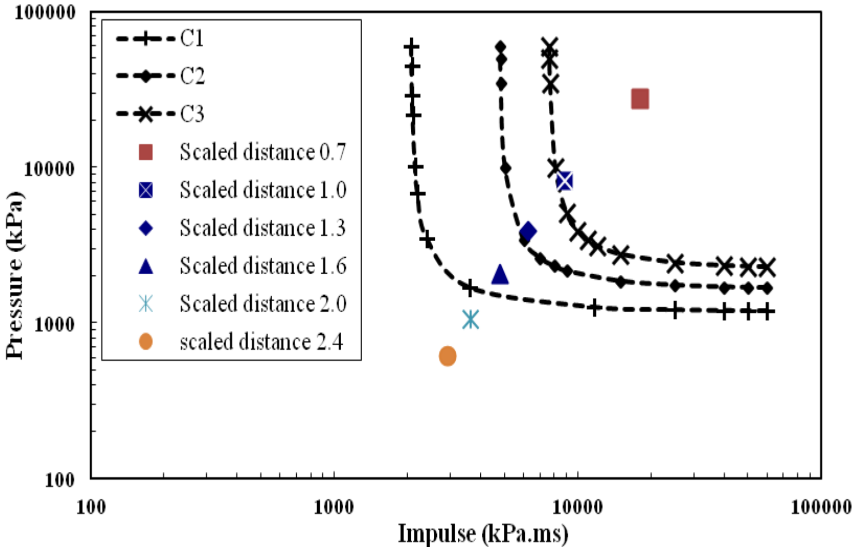

Figure 3 P-I diagrams of the three example unstrengthened columns constructed with the damage level, D=0.8

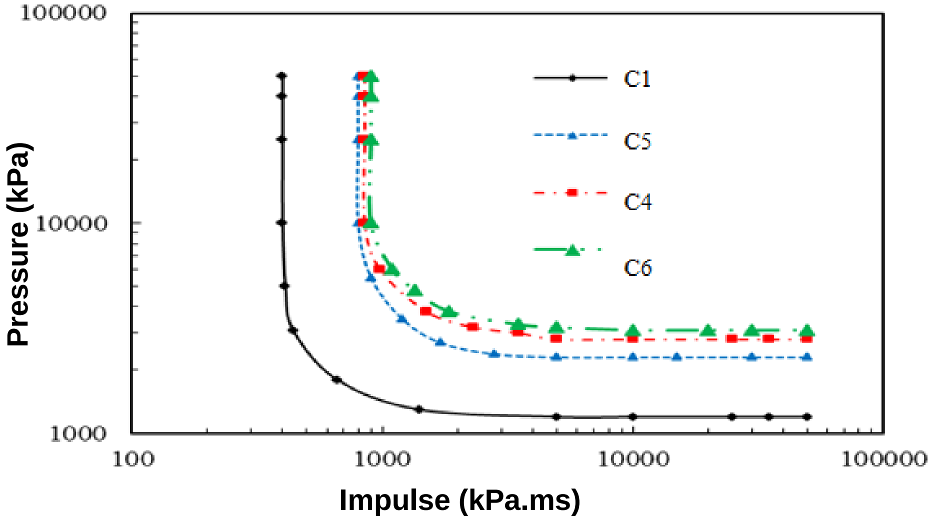

Figure 4 P-I diagrams of the three example FRP strengthened columns constructed with the damage level, D=0.8

Table 3 summarized P_o and I_o for all columns where for C1, P_o and I_o values are 1178 kPa and 2070 kPa.ms, for C2, the value of P_o and I_o are 1635 kPa and 4813 kPa.ms, while for C3, the value of P_o and I_o are 2200 kPa and 7646 kPa.ms. In case of FRP strengthened RC columns, P_o and I_o for C4, C5 and C6 are 2814 kPa and 950 kPa.ms, 2250 kPa and 800 kPa.ms and 3145 kPa and 1040 kPa.ms, respectively. The increases of column size can increases the blast loadings as well as by utilizing combination FRP wrap and FRP strip in strengthening the RC column.

Table 3 Pressure and impulse asymptotes of the columns corresponding to the high level of damage, D = 0.8

Column	D=0.8	
	P_O (kPa)	I_O (kPa.ms)
C1	1178	2070
C2	1635	4813
C3	2200	7646
C4	2814	950
C5	2250	800
C6	3145	1040

■3.0 FAILURE PROBABILITIES ANALYSIS FOR RC COLUMN DAMAGE

Two states of structural system are considered in probability analysis to determine level of RC columns failure [4]. They are defined by a performance function g(X) as,

$$g(X) > 0, \quad \text{safe from failure} \tag{16}$$

$$g(X) \leq 0, \quad \text{damage state} \tag{17}$$

Where limit state function is defined as,

$$g(X) = D(\rho_s, \rho, f'_c, h, b, H, P_r, t_d) - D^*(P_r, t_d) \tag{18}$$

The distance D and D* are calculated by utilizing Equations (19) and (20) as follows,

$$D(P_i, I_i) = (P_i^2 + I_i^2)^{1/2} \tag{19}$$

$$D^*(P_r, I_r) = (P_r^2 + I_r^2) \tag{20}$$

Pi and *Ii* are pressure and impulse intersection. They can be determined as follows

$$I_i = [\, I_0 + [\, (\, I_0^2 + 4[\, 12(\, (P_0/2) + (I_0/2)\,)^{1.5} + P_0\,]\, (I_r/P_r)\,]^{1/2}\,]\, /2 \tag{21}$$

$$P_i = (P_r/I_r)\, I_I \tag{22}$$

While Equations (23) and (24) are utilized to calculate reflected pressure P_r and reflected impulse I_r .

$$\log_{10} P_r = 3.651 - 3.018 \log_{10}(z) + 0.1967 [\log_{10}(z)]^2 + 0.8873 [\log_{10}(z)]^3 - 0.3795 [\log_{10}(z)]^4 \tag{23}$$

$$I_r = (1/2) P_r t_d \tag{24}$$

$$\log_{10} t_d / W^{1/3} = -0.00307 + 1.2186 \log_{10}(z) - 0.5207 [\log_{10}(z)]^2 - 0.2835 [\log_{10}(z)]^3 + 0.2132 [\log_{10}(z)]^4 \tag{25}$$

Parameter values for three type of columns as in Tables 1 and 2 are substituted into Equations (3) until (8) for RC columns with and without FRP strengthening to determine pressure asymptote P_O, impulse asymptote I_O and scaled distance z in order to solve Equations (21) until (25). Where α_1, α_2, α_3, α_4, α_5 and α_6 are 0 for unstrengthened RC columns, while Equations (9) until (14) are utilized to determine α_1, α_2, α_3, α_4, α_5 and α_6 for FRP strengthened RC columns.

RC columns damage probabilities with different z and level of damages are evaluated using reliability index method. In design approach and analysis that base on reliability, reliability index, β measurement is used. In this case, β is functioning to show reliability level that being used in analysis. In practical structural analysis, β can be calculated using reliability theory and knowledge of first and second moment that statistically characterise i.e. min and coefficient of variant (COV) values for both strength and load variables. It is derived as

$$\beta = (U_{\text{strength}} - U_{\text{explosion}}) / (COV_{\text{strength}} + COV_{\text{explosion}}) \tag{26}$$

where, $U_{strength}$, $U_{explsoion}$, $COV_{strength}$ and $COV_{explosion}$ are min strength, min explosion, strength coefficient of variant and explosion coefficient of explosion, respectively.

For both variable and linear function, reliability index β can be defined as shortest distance from point of origin to failure line [13] as shown in Figure 5 below. Reliability index according to this definition usually referred to as Hasofer-and-Lind index [14].

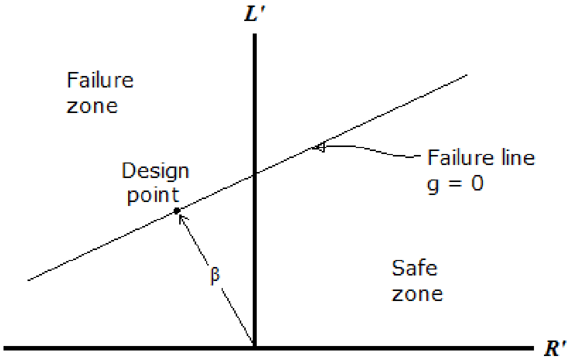

Figure 5 Relationship between β and design point [13]

Value of β obtained is used as z to find $\Phi(z)$ in Cumulative Normal Distribution. Where $\Phi(z)$ is cumulative probability distribution function for the normal distribution. The failure probabilities of unstrengthened and FRP strengthened RC columns is determined as follows

$$\text{Failure Probability} = 1 - \Phi(z) \tag{27}$$

Equation (27) assumes all random variables in the equation of limit state have a normal probability distribution function and performance is linear. In this case, the error in estimating the probability of failure is small. Thus, for all practical purposes, Equation (27) can be used to assess with sufficient accuracy [15].

■4.0 PREDICTION OF BLAST DAMAGE USING PROBABILITY ANALYSIS

The failure probabilities of the columns corresponding to column collapse (D = 0.8) are estimated by assuming a 1000 kg TNT equivalent explosion at different standoff distances. Figure 6 shows the failure probabilities of unstrengthened RC columns. As shown, C1, C2 and C3 will collapse when the column probability of the column is almost 1.0 i.e. when scaled distance are 1.5 m/kg$^{-1/3}$, 0.8 m/kg$^{-1/3}$, 0.6 m/kg$^{-1/3}$, respectively. This indicates reliability analysis gives range of scaled distances with different probabilities of column collapse.

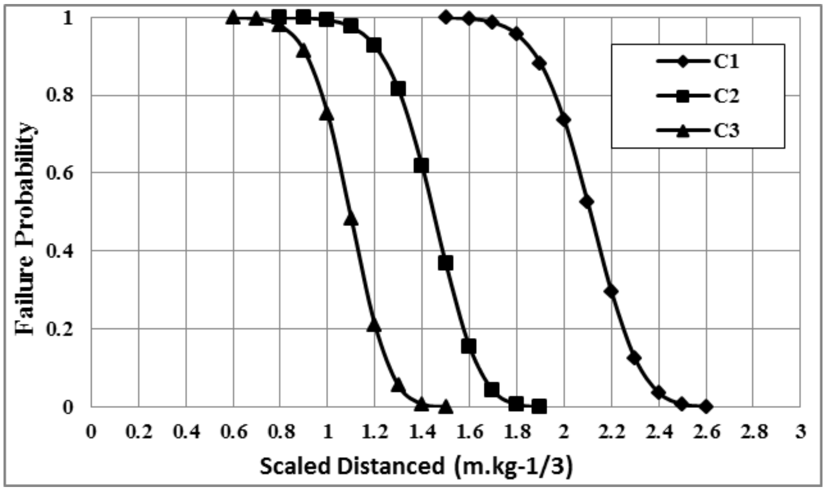

Figure 6 Probability of failure against distance scale for structure C1, C2 and C3

Figure 7 shows the probability of failure for C1 and C4. C4 is due to the strengthening of C1 by FRP wrap and the column details as in Tables 1 and 2. The strengthening measure increases the column blast resistant capacity and improves the C4 to withstand the 1000 kg TNT explosion until scaled distance 1.2 m/kg$^{-1/3}$ and has a safe limit of the distance scale 2.3 m/kg$^{1/3}$ and above, while the columns C1 shown safe limit on the distance scale 2.5 m/kg$^{1/3}$ and collapse at 1.5 m/kg$^{-1/3}$.

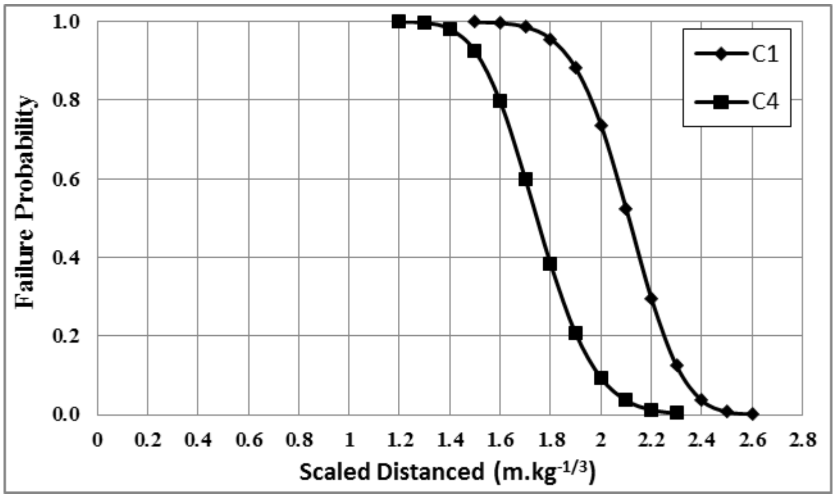

Figure 7 Probability of failure against distance scale for structure C1 and C4

■5.0 CONCLUSIONS

In this study, the failure probabilities of different RC columns with or without FRP strengthening subjected to blast load are determined. The empirical formulae derived from series of verified numerical simulations is used to develop probability of RC column damage at difference scaled distances. A comparison of different size of columns and FRP strengthening techniques is carried out to identify the best column in resisting the explosive loads.

The results obtained show that the statistical variations of blast loadings against scaled distance influence the damage to each columns by taking into account the different size of columns and the addition of FRP materials. C3 with larger dimension can sustain the blast loads until scaled distance 1.2 m/kg$^{-1/3}$, while the FRP strengthening increases the column blast load resistant capacity until 1.2 m/kg$^{-1/3}$ for column size C1. This indicates reliability analysis gives range of scaled distances with different probabilities of column collapse.

Acknowledgement

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